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Srivastava et al.

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(54) **CROSS MODULE REPRESENTATION OF HETEROGENEOUS PROGRAMS**

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(58) **Field of Search** 717/147, 141–146, 717/153–158, 148, 149, 152–154, 159, 161

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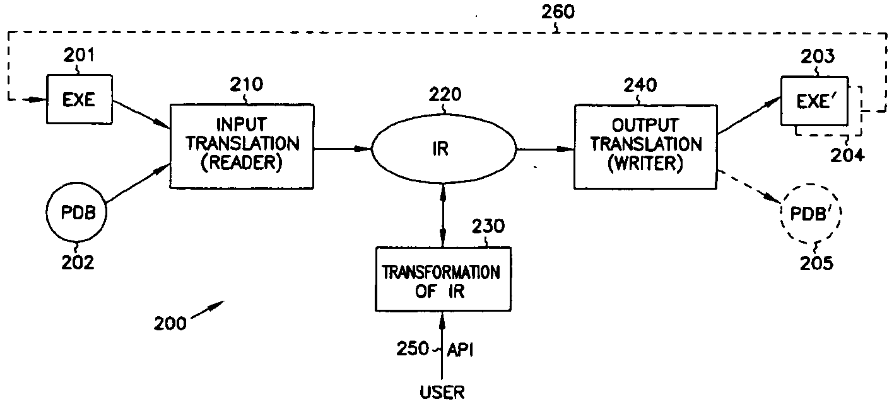
(57) **ABSTRACT**

An output translator provides for cross module representations of components within a heterogeneous program by translating modifying a platform-neutral intermediate representation (IR) of the program into platform-specific instructions for different architectures. The intermediate representation is hierarchy of base elements that correspond to instructions, code blocks, procedures and components within the program. Blocks of instructions that were originally written for one architecture can be translated from the intermediate representation into platform-specific instructions for a different architecture. The output translator provides any necessary code to interface contiguous code blocks that are emitted in different instruction sets.

24 Claims, 11 Drawing Sheets



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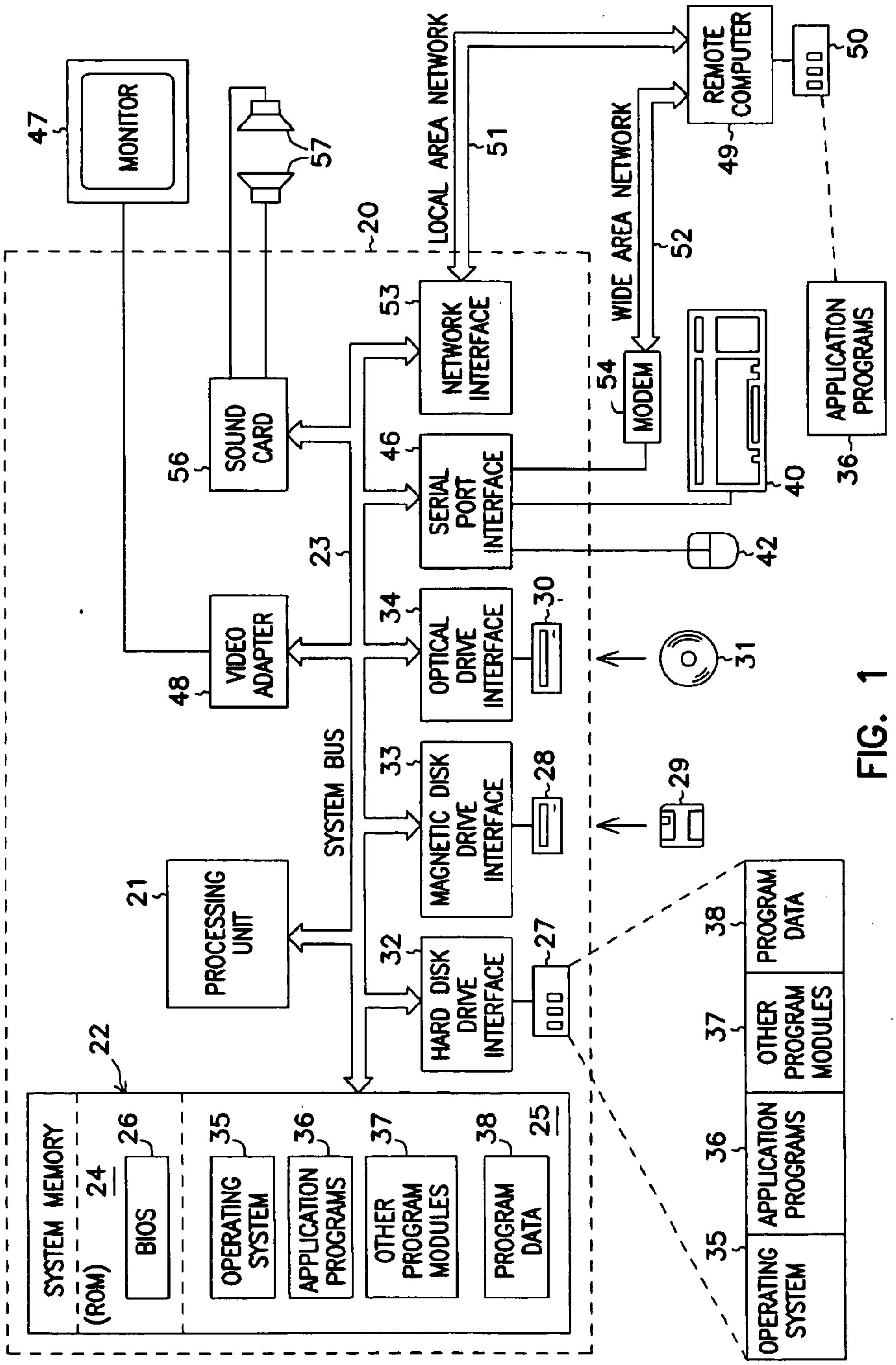

MONITOR
47
57
20
LOCAL AREA NETWORK
51
REMOTE COMPUTER
49
50
WIDE AREA NETWORK
52
SOUND CARD
56
NETWORK INTERFACE
53
MODEM
54
SERIAL PORT INTERFACE
46
40
APPLICATION PROGRAMS
36
VIDEO ADAPTER
48
23
OPTICAL DRIVE INTERFACE
34
30
31
42
SYSTEM BUS
PROCESSING UNIT
21
MAGNETIC DISK DRIVE INTERFACE
33
28
29
HARD DISK DRIVE INTERFACE
32
27
22
SYSTEM MEMORY
(ROM)
24
BIOS
26
OPERATING SYSTEM
35
APPLICATION PROGRAMS
36
OTHER PROGRAM MODULES
37
PROGRAM DATA
38
25
OPERATING SYSTEM
35
APPLICATION PROGRAMS
36
OTHER PROGRAM MODULES
37
PROGRAM DATA
38

FIG. 1

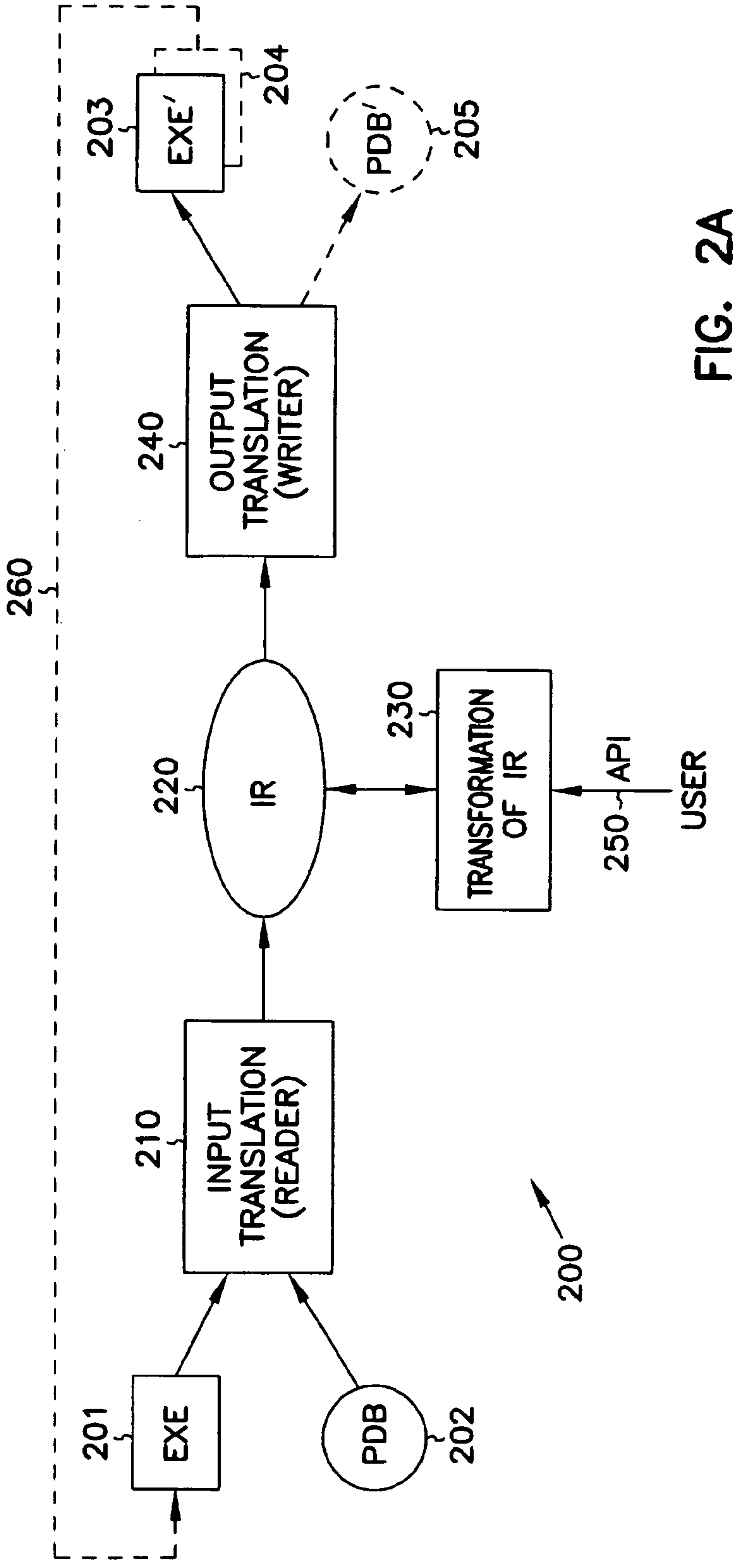

200
201
EXE
202
PDB
210
INPUT TRANSLATION (READER)
220
IR
230
TRANSFORMATION OF IR
250
API
USER
240
OUTPUT TRANSLATION (WRITER)
203
EXE'
204
205
PDB'
260

FIG. 2A

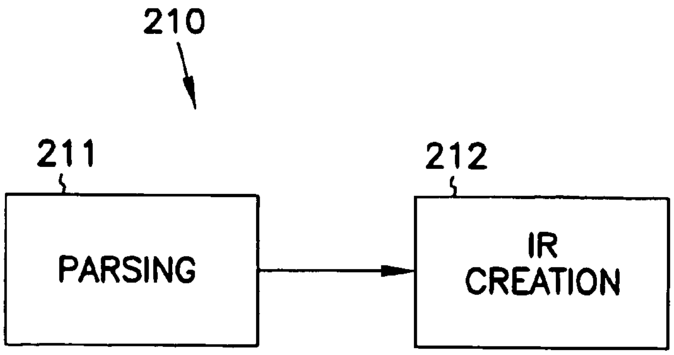


FIG. 2B

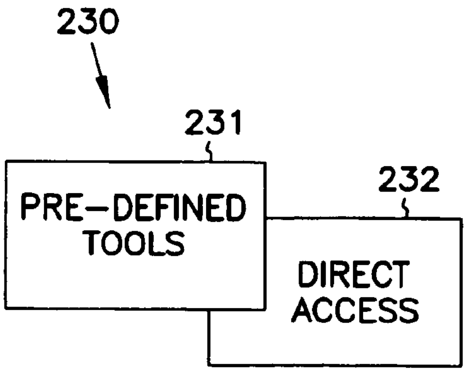


FIG. 2C

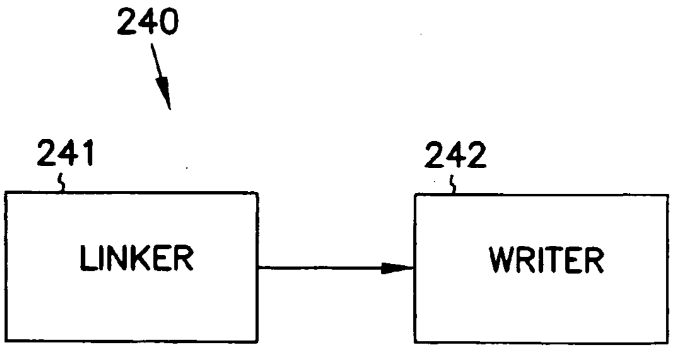


FIG. 2D

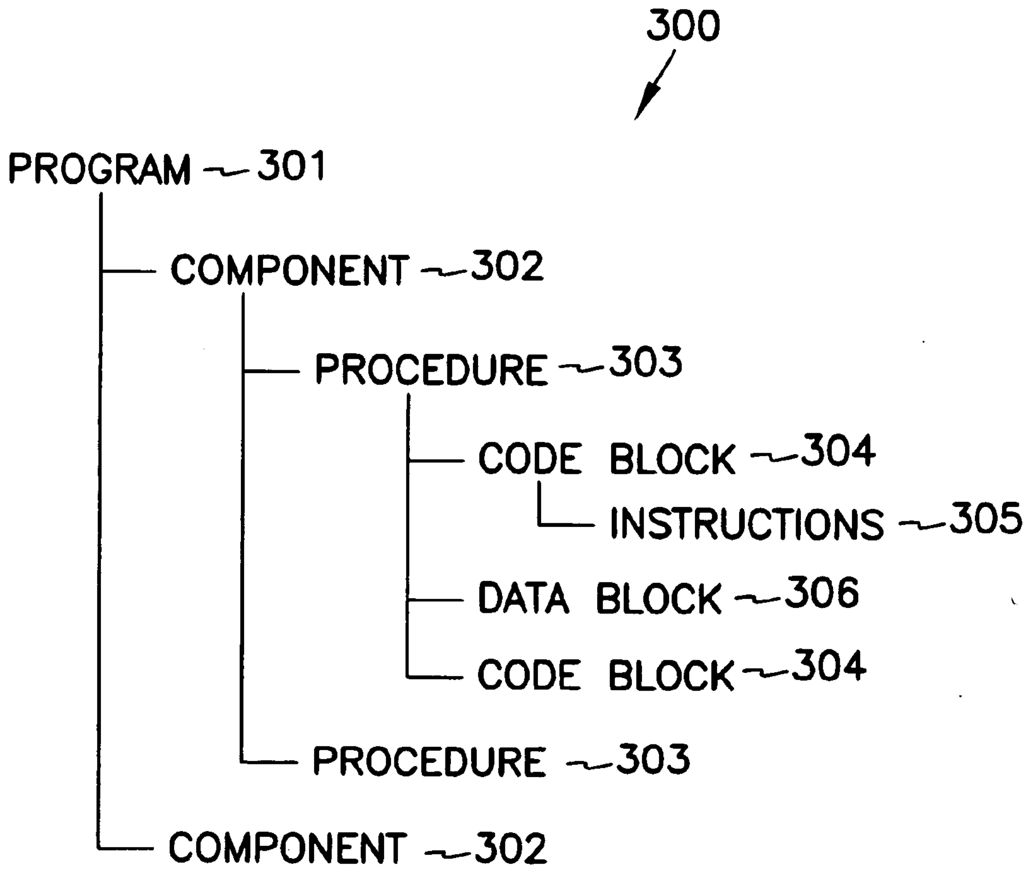

300
PROGRAM 301
COMPONENT 302
PROCEDURE 303
CODE BLOCK 304
INSTRUCTIONS 305
DATA BLOCK 306
CODE BLOCK 304
PROCEDURE 303
COMPONENT 302

FIG. 3

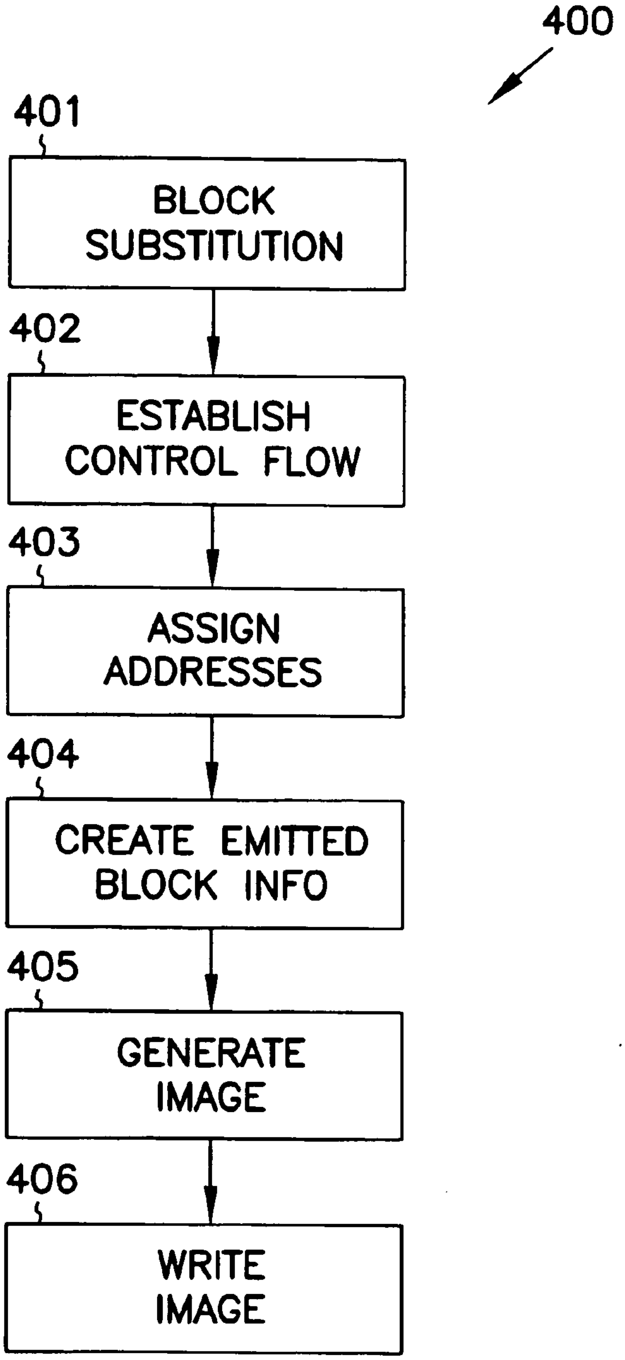

400
401
BLOCK SUBSTITUTION
402
ESTABLISH CONTROL FLOW
403
ASSIGN ADDRESSES
404
CREATE EMITTED BLOCK INFO
405
GENERATE IMAGE
406
WRITE IMAGE

FIG. 4A

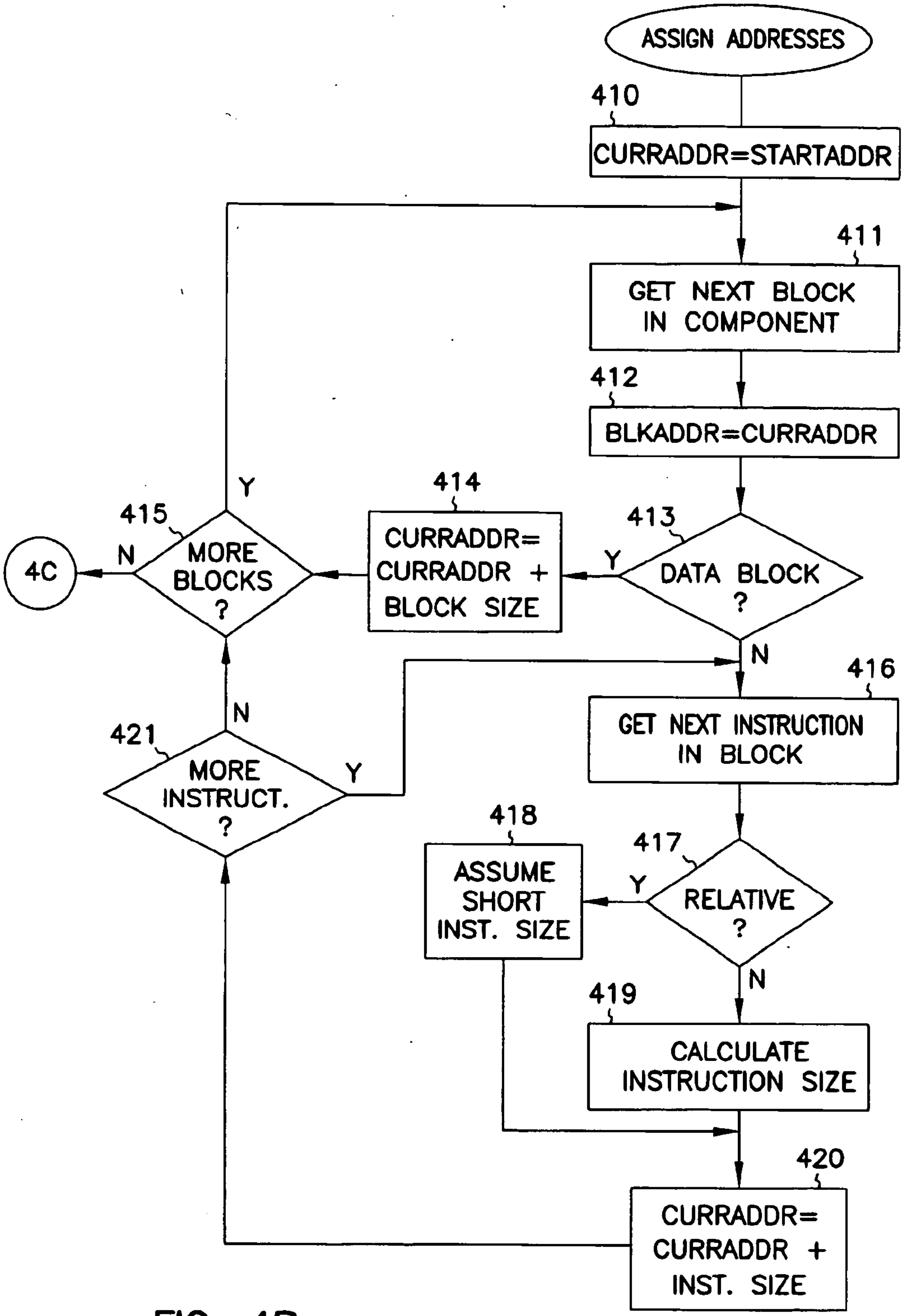
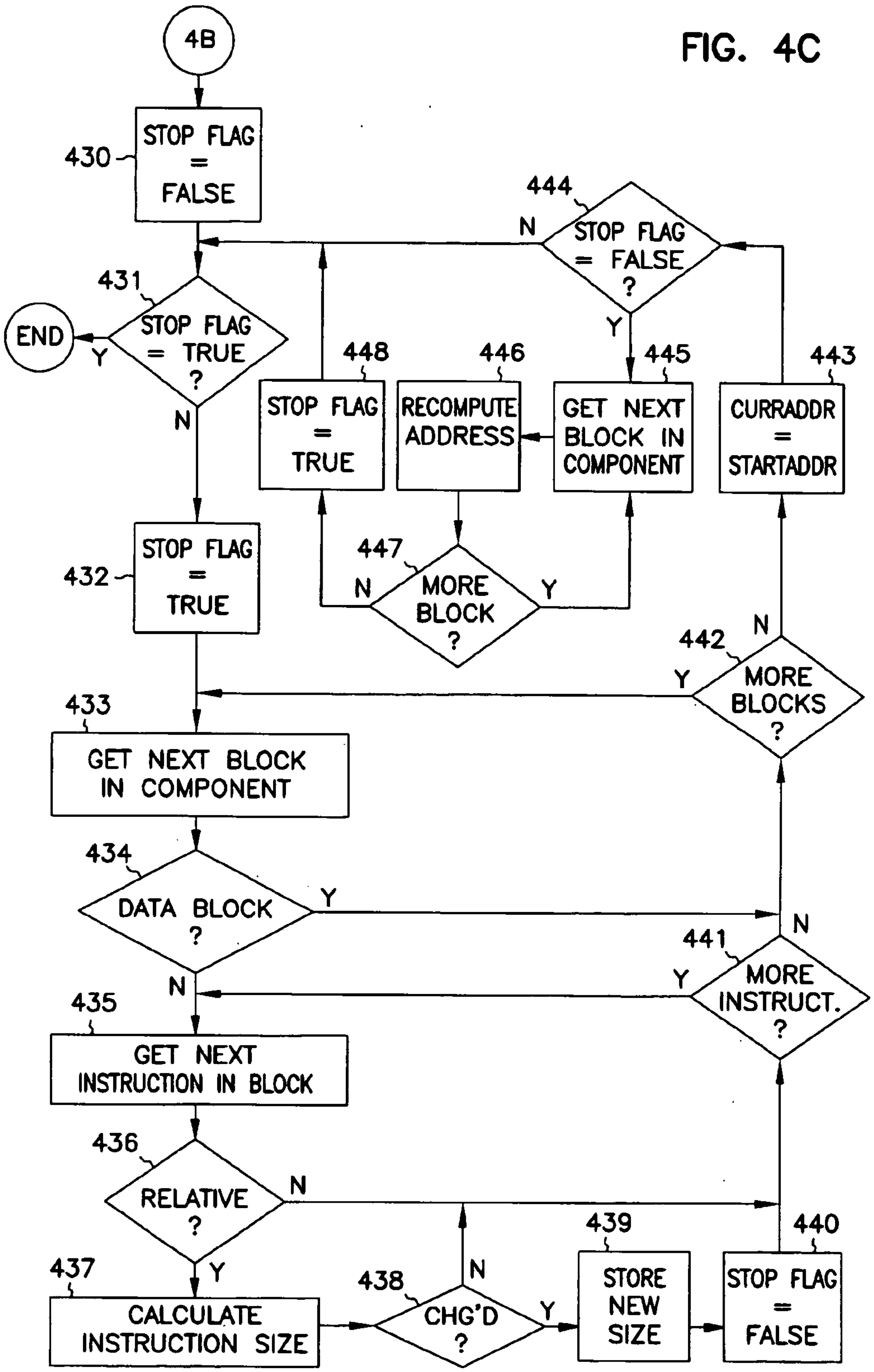

ASSIGN ADDRESSES
410
CURRADDR=STARTADDR
411
GET NEXT BLOCK IN COMPONENT
412
BLKADDR=CURRADDR
413
DATA BLOCK ?
Y
414
CURRADDR= CURRADDR + BLOCK SIZE
415
MORE BLOCKS ?
Y
N
4C
N
416
GET NEXT INSTRUCTION IN BLOCK
417
RELATIVE ?
Y
418
ASSUME SHORT INST. SIZE
N
419
CALCULATE INSTRUCTION SIZE
420
CURRADDR= CURRADDR + INST. SIZE
421
MORE INSTRUCT. ?
Y
N

FIG. 4B

FIG. 4C


4B
430
STOP FLAG = FALSE
431
STOP FLAG = TRUE ?
END
Y
N
432
STOP FLAG = TRUE
433
GET NEXT BLOCK IN COMPONENT
434
DATA BLOCK ?
Y
N
435
GET NEXT INSTRUCTION IN BLOCK
436
RELATIVE ?
N
Y
437
CALCULATE INSTRUCTION SIZE
438
CHG'D ?
N
Y
439
STORE NEW SIZE
440
STOP FLAG = FALSE
441
MORE INSTRUCT. ?
Y
N
442
MORE BLOCKS ?
Y
N
443
CURRADDR = STARTADDR
444
STOP FLAG = FALSE ?
N
Y
445
GET NEXT BLOCK IN COMPONENT
446
RECOMPUTE ADDRESS
447
MORE BLOCK ?
N
Y
448
STOP FLAG = TRUE

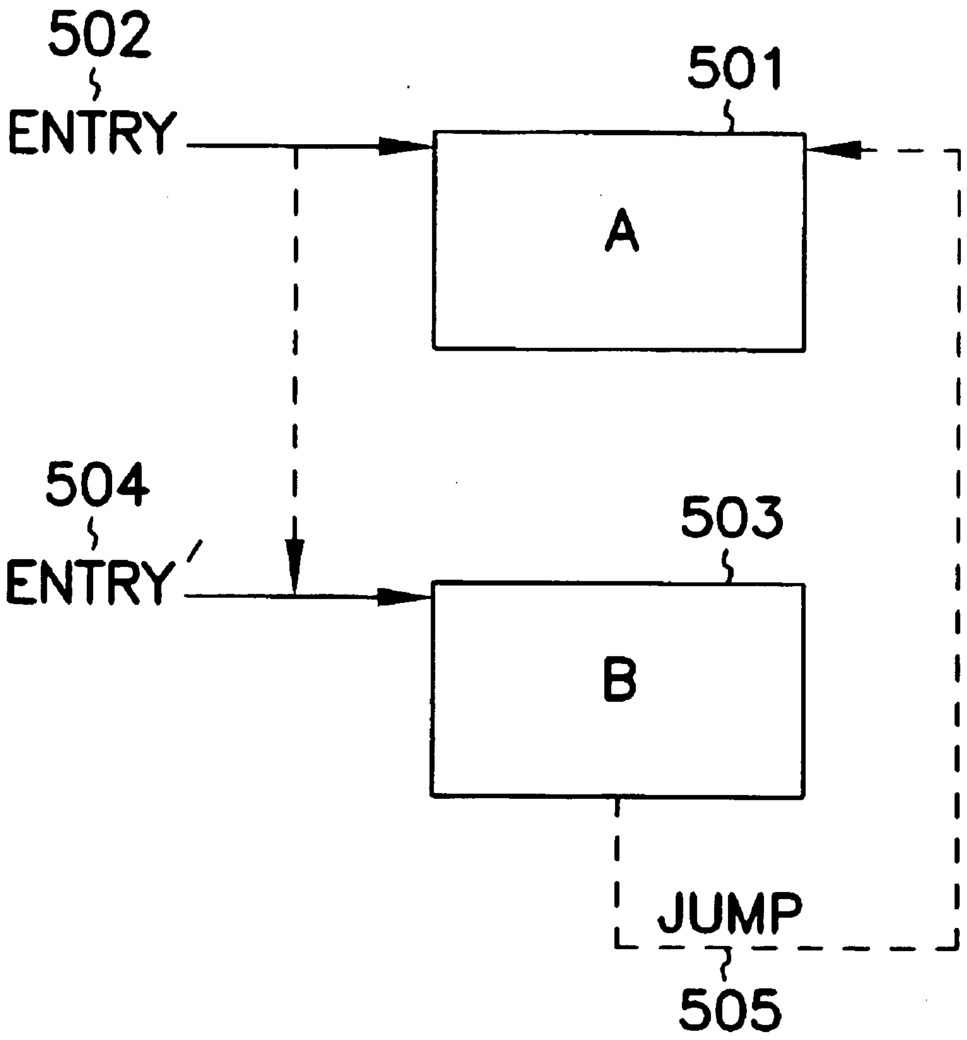


FIG. 5

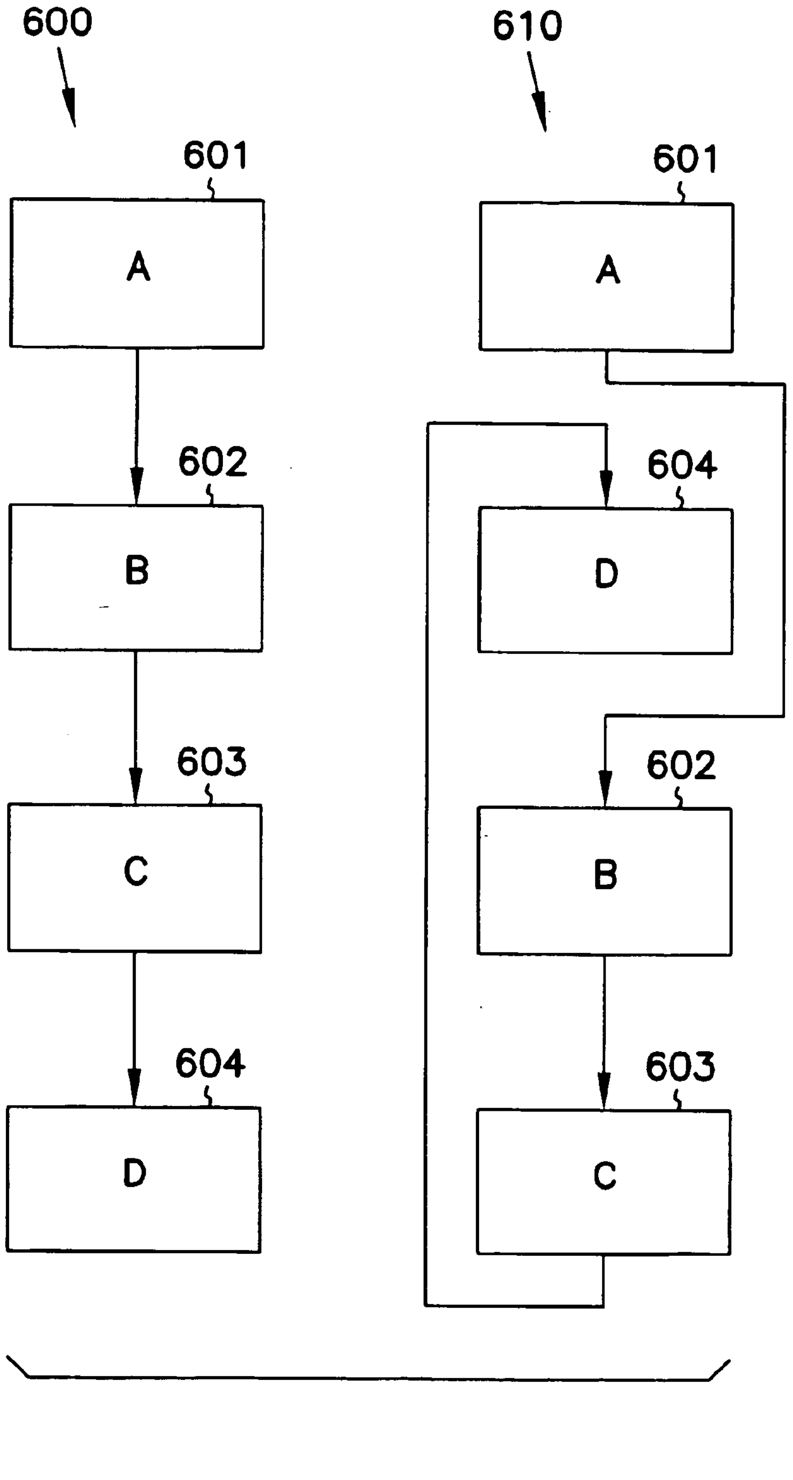


FIG. 6A

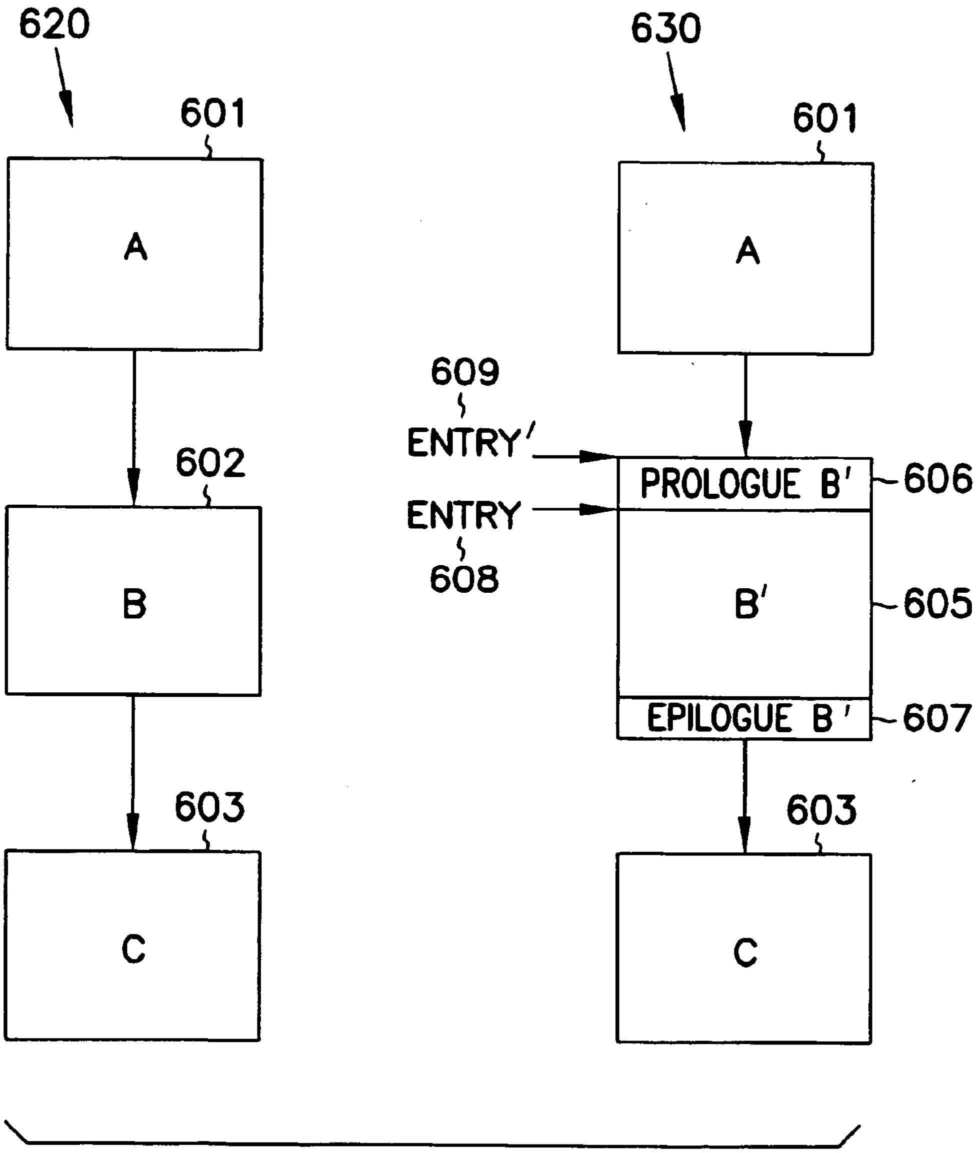

620
601
A
602
B
603
C
630
601
A
609
ENTRY'
ENTRY
608
PROLOGUE B'
606
B'
605
EPILOGUE B'
607
603
C

FIG. 6B

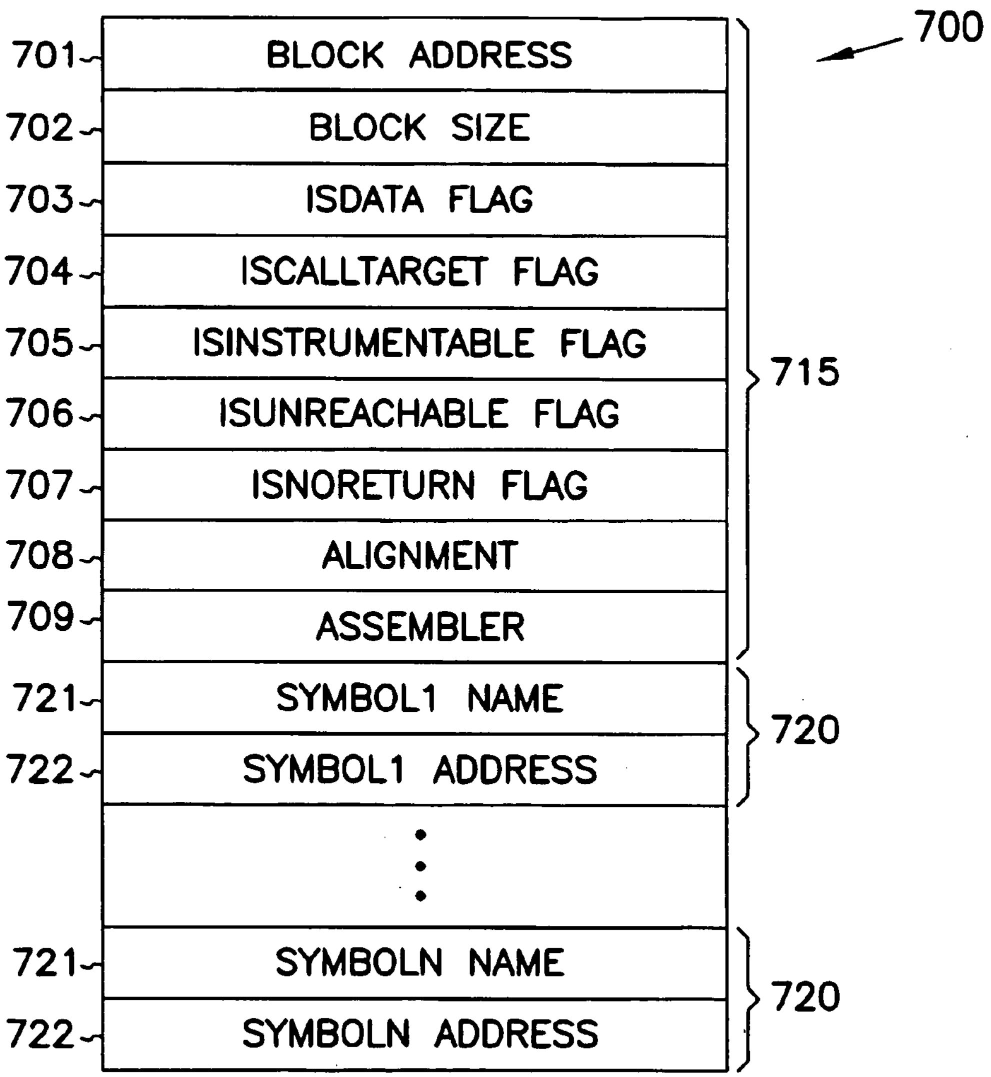

700
701
BLOCK ADDRESS
702
BLOCK SIZE
703
ISDATA FLAG
704
ISCALLTARGET FLAG
705
ISINSTRUMENTABLE FLAG
706
ISUNREACHABLE FLAG
707
ISNORETURN FLAG
708
ALIGNMENT
709
ASSEMBLER
715
721
SYMBOL1 NAME
722
SYMBOL1 ADDRESS
720
721
SYMBOLN NAME
722
SYMBOLN ADDRESS
720

FIG. 7

CROSS MODULE REPRESENTATION OF HETEROGENEOUS PROGRAMS

RELATED APPLICATIONS

The present application is related to U.S. Patent applications entitled "Translation And Transformation of Heterogeneous Programs" (U.S. patent application Ser. No. 09/343,805), "Instrumentation and Optimization Tools for Heterogeneous Programs" (U.S. patent application Ser. No. 09/343,298), "Application Program Interface for Transforming Heterogeneous Programs" (U.S. patent application Ser. No. 09/343,276), and "Shared Library Optimization for Heterogeneous Programs" (U.S. patent application Ser. No. 09/343,279), filed on the same day as the present application and assigned to the same assignee.

FIELD OF THE INVENTION

This invention relates generally to programming tools, and more particularly to translating code between computer architectures.

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BACKGROUND OF THE INVENTION

In a new programming paradigm, a program is now a collection of components. Each component publishes an interface without exposing its inner details. Thus, a component can internally exist in any form: Intel x86 binary, Intel IA-64 binary, Visual Basic (VB) byte codes, Java class files, or any Virtual Machine (VM) binary. A heterogeneous program consists of components in different forms. Heterogeneous programs already exist in some environments: in the Microsoft Windows 32-bit environment, a Visual Basic program is compiled into VB byte codes that can call native-compiled functions in a separate dynamic linked library. Similarly Java class files can call native functions. Intel's IA-64 architecture allows IA-64 code to co-exist with x86 code.

To understand the behavior of a heterogeneous program, all its components, regardless of their form, have to be instrumented and analyzed in the same framework, otherwise, only partial information will be collected. It is important to note that systems that have been ported to several architectures are not sufficient to handle heterogeneous programs. For example, a system for VB byte codes that has been ported to x86, cannot provide a complete execution time analysis of a heterogeneous program consisting of VB byte codes and native x86 because each system operates in isolation on its own input.

Further, a heterogeneous program may consist of heterogeneous components. A heterogeneous component is a single component consisting of routines in different instruction sets. As the interface is well defined, components internally can use any instruction set. Each instruction set has its own advantages such as execution time, portability, and size.

All previous systems have been designed for homogeneous programs: conventional programs consisting of components in the same form. Some systems have been targeted to different architectures, but cannot work with heterogeneous programs. None of these systems can generate a heterogeneous component.

A large number of systems have been developed to help analyze and optimize homogeneous programs. The creation of "Pixie" by MIPS Computers Systems, Inc. in 1986 started a class of basic block counting tools by inserting predetermined sequence of instructions to record execution frequencies of basic blocks. "Epoxie" extended the technique by using relocations to eliminate dynamic translation overheads. David W. Wall. Systems for late code modification, in Code Generation—Concept, Tools Techniques, pp. 275–293, (Robert Giegrich and Susan L. Graham, eds, 1992). "QPT" further extended the technique by constructing spanning trees to reduce the number of basic blocks that are instrumented. James Larus and Thomas Ball, Rewriting executable files to measure program behavior, Software, Practice and Experience, vol. 24, no. 2, pp 197–218 (1994). "Purify" instruments memory references to detect out-of-bounds memory accesses and memory leaks. Reed Hastings and Bob Joyce, Purify: Fast Detection of Memory Leaks and Access Errors, Proceedings of Winter Usenix Conference, January 1992.

"OM" allowed general transformations to be applied to a binary by converting the binary to an intermediate representation that can be easily manipulated. Amitabh Srivastava and David Wall, A Practical System for Intermodule Code Optimization at Link Time, Journal of Programming Language, 1(1):1–18 (1993). OM has been implemented on MIPS, DEC Alpha and Intel x86 architectures. "EEL" uses a similar technique and provides an editing library for Sun SPARC architectures. James R. Larus and Eric Schnarr, EEL: Machine-Independent Executable Editing, Proceedings of SIGPLAN' 95 Conference on Programming Language Design and Implementation (1995). "Alto" and "Spike" are optimizers for the DEC Alpha architectures. K. De Bosschere and S. Debray, Alto: a Link-Time Optimizer for the DEC Alpha. Technical Report TR-96-16, Computer Science Department, University of Arizona (1996). David W. Goodwin, Interprocedural Dataflow Analysis in an Executable Optimizer, Proceedings of SIGPLAN' 97 Conference on Programming Language Design and Implementation (1997).

"ATOM" extended OM by providing a flexible instrumentation interface for the DEC Alpha and Intel x86 systems. Amitabh Srivastava and Alan Eustace, ATOM: A System for Building Customized Program Analysis Tools, Proceedings of SIGPLAN' 94 Conference on Programming Language Design and Implementation (1994). However, ATOM does not allow modifications to a binary. "Etch" provided a similar system for x86 and "BIT" for Java byte codes. T. Romer, G. Voelker, D. Lee, A. Wolman, W. Wong, H. Levy, B. Chen, and B. Bershad, Instrumentation and Optimization of Win32/Intel Executables Using Etch, Proceedings of the USENIX Windows NT Workshop (1997). Han Lee and Benjamin Zorn, BIT: A Tool for instrumenting Java bytecodes. Proceedings of the 1997 USENIX Symposium on Internet Technologies and Systems (1997).

None of these systems work on heterogeneous programs. Some of them have been ported to multiple architecture but they provide only a partial view when applied to heterogeneous programs as each implementation operates on its input in isolation. Although OM builds a symbolic representation, the representation was primarily designed for applying arbitrary transformations and is not sufficient to handle heterogeneous programs. None of these systems can generate heterogeneous components. ATOM provides a flexible interface for instrumentation only.

Because a heterogeneous program provides efficiencies that cannot be achieved by a homogeneous program, a mechanism is needed that can convert portions of a homogeneous program into a different instruction set to optimize the execution of the program or produce more compact code. Furthermore, the ability to apply the same mechanism to an existing heterogeneous program to produce further optimization is also desirable.

SUMMARY OF THE INVENTION

The above-mentioned shortcomings, disadvantages and problems are addressed by the present invention, which will be understood by reading and studying the following specification.

An output translator provides for cross module representations of components within a heterogeneous program by enabling a code block in a component to be translated from an platform-neutral intermediate representation of the program into a set of platform-specific instructions that are directed to a different architecture than that for which the code block was originally written. The output translator provides any necessary prologue and/or epilogue code to interface contiguous code blocks that are emitted in different instruction sets. For an architecture that has both short and long forms for instructions, one aspect of the output translator initially assumes the emitted instruction will be in its short form and only substitutes the long form when required. The output translator also enables the substitution of one code block for another, automatically adjusting entry points as required. Changes in the order of code blocks within the component are accommodated while preserving, and optimally optimizing, the original control flow.

Because the architecture of a code block can be changed when it is translated from the intermediate representation, a user can create a more efficient heterogeneous program from a homogeneous program or can optimize an existing heterogeneous program by specifying an architecture that supplies a desired characteristic, such as speed or compactness of code. Even without changing platform, the output translator can produce more compact code than originally generated by a compiler because the output translator uses short forms for instructions as a default size where the majority of compilers default to long forms. Additionally, the output translator can emit instructions for a new platform for which a compiler is not yet been written, allowing early testing and evaluation of the architecture.

The present invention describes systems, clients, servers, methods, and computer-readable media of varying scope. In addition to the aspects and advantages of the present invention described in this summary, further aspects and advantages of the invention will become apparent by reference to the drawings and by reading the detailed description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of the hardware and operating environment in conjunction with which embodiments of the invention may be practiced;

FIG. 2A is a diagram illustrating a system-level overview of an exemplary embodiment of the invention;

FIGS. 2B, 2C and 2D are diagrams illustrating additional details of the processes shown in FIG. 2A;

FIG. 3 is a diagram of an intermediate representation hierarchy used by the exemplary embodiment of FIG. 2A;

FIG. 4A is a flowchart of an output translator method to be performed by a computer according to an exemplary embodiment of the invention;

FIGS. 4B and 4C are flowcharts of details of the exemplary embodiment of the output translator method of FIG. 4A;

FIG. 5 is a diagram of a redirected block created by the output translator method of FIG. 4A;

FIGS. 6A and 6B are diagrams control flow changes created by the output translator method of FIG. 4A; and

FIG. 7 is a diagram of an emitted block data structure created by the output translator method of FIG. 4A.

DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description of exemplary embodiments of the invention, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific exemplary embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that logical, mechanical, electrical and other changes may be made without departing from the spirit or scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims.

The detailed description is divided into four sections. In the first section, the hardware and the operating environment in conjunction with which embodiments of the invention may be practiced are described. In the second section, a system level overview of the invention is presented. In the third section, methods and data structures for an exemplary embodiment of the invention are provided. Finally, in the fourth section, a conclusion of the detailed description is provided.

Hardware and Operating Environment

FIG. 1 is a diagram of the hardware and operating environment in conjunction with which embodiments of the invention may be practiced. The description of FIG. 1 is intended to provide a brief, general description of suitable computer hardware and a suitable computing environment in conjunction with which the invention may be implemented. Although not required, the invention is described in the general context of computer-executable instructions, such as program modules, being executed by a computer, such as a personal computer. Generally, program modules include routines, programs, objects, components, data structures, etc., that perform particular tasks or implement particular abstract data types.

Moreover, those skilled in the art will appreciate that the invention may be practiced with other computer system configurations, including hand-held devices, multiprocessor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, and the like. The invention may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

The exemplary hardware and operating environment of FIG. 1 for implementing the invention includes a general purpose computing device in the form of a computer **20**, including a processing unit **21**, a system memory **22**, and a system bus **23** that operatively couples various system components, including the system memory **22**, to the processing unit **21**. There may be only one or there may be more than one processing unit **21**, such that the processor of computer **20** comprises a single central-processing unit (CPU), or a plurality of processing units, commonly referred to as a parallel processing environment. The computer **20** may be a conventional computer, a distributed computer, or any other type of computer; the invention is not so limited.

The system bus **23** may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures. The system memory may also be referred to as simply the memory, and includes read only memory (ROM) **24** and random access memory (RAM) **25**. A basic input/output system (BIOS) **26**, containing the basic routines that help to transfer information between elements within the computer **20**, such as during start-up, is stored in ROM **24**. The computer **20** further includes a hard disk drive **27** for reading from and writing to a hard disk, not shown, a magnetic disk drive **28** for reading from or writing to a removable magnetic disk **29**, and an optical disk drive **30** for reading from or writing to a removable optical disk **31** such as a CD ROM or other optical media.

The hard disk drive **27**, magnetic disk drive **28**, and optical disk drive **30** are connected to the system bus **23** by a hard disk drive interface **32**, a magnetic disk drive interface **33**, and an optical disk drive interface **34**, respectively. The drives and their associated computer-readable media provide nonvolatile storage of computer-readable instructions, data structures, program modules and other data for the computer **20**. It should be appreciated by those skilled in the art that any type of computer-readable media which can store data that is accessible by a computer, such as magnetic cassettes, flash memory cards, digital video disks, Bernoulli cartridges, random access memories (RAMs), read only memories (ROMs), and the like, may be used in the exemplary operating environment.

A number of program modules may be stored on the hard disk, magnetic disk **29**, optical disk **31**, ROM **24**, or RAM **25**, including an operating system **35**, one or more application programs **36**, other program modules **37**, and program data **38**. A user may enter commands and information into the personal computer **20** through input devices such as a keyboard **40** and pointing device **42**. Other input devices (not shown) may include a microphone, joystick, game pad, satellite dish, scanner, or the like. These and other input devices are often connected to the processing unit **21** through a serial port interface **46** that is coupled to the system bus, but may be connected by other interfaces, such as a parallel port, game port, or a universal serial bus (USB). A monitor **47** or other type of display device is also connected to the system bus **23** via an interface, such as a video adapter **48**. In addition to the monitor, computers typically include other peripheral output devices (not shown), such as speakers and printers.

The computer **20** may operate in a networked environment using logical connections to one or more remote computers, such as remote computer **49**. These logical connections are achieved by a communication device coupled to or a part of the computer **20**; the invention is not limited to a particular type of communications device. The remote computer **49** may be another computer, a server, a router, a network PC, a client, a peer device or other common network node, and typically includes many or all of the elements described above relative to the computer **20**, although only a memory storage device **50** has been illustrated in FIG. **1**. The logical connections depicted in FIG. **1** include a local-area network (LAN) **51** and a wide-area network (WAN) **52**. Such networking environments are commonplace in offices, enterprise-wide computer networks, intranets and the Internet.

When used in a LAN-networking environment, the computer **20** is connected to the local network **51** through a network interface or adapter **53**, which is one type of communications device. When used in a WAN-networking environment, the computer **20** typically includes a modem **54**, a type of communications device, or any other type of communications device for establishing communications over the wide area network **52**, such as the Internet. The modem **54**, which may be internal or external, is connected to the system bus **23** via the serial port interface **46**. In a networked environment, program modules depicted relative to the personal computer **20**, or portions thereof, may be stored in the remote memory storage device. It is appreciated that the network connections shown are exemplary and other means of and communications devices for establishing a communications link between the computers may be used.

The hardware and operating environment in conjunction with which embodiments of the invention may be practiced has been described. The computer in conjunction with which embodiments of the invention may be practiced may be a conventional computer, a distributed computer, or any other type of computer; the invention is not so limited. Such a computer typically includes one or more processing units as its processor, and a computer-readable medium such as a memory. The computer may also include a communications device such as a network adapter or a modem, so that it is able to communicatively couple to other computers.

System Level Overview

A system level overview of the operation of an exemplary embodiment of the invention is described by reference to FIGS. 2A–D. A heterogeneous program contains multiple executable components, such as main program code and shared libraries, written for different computer architectures (platforms) or programming languages. FIG. 2A shows a system **200** that translates and transforms components in a heterogeneous program. The system **200** comprises an input translator (reader) **210**, a transformation module **230**, and an output translator (writer) **240**. All three modules work with a high-level abstraction of a heterogeneous program, referred to as an "intermediate representation" (IR) **220**. The IR is a set of pseudo-instructions for a stack-based logical machine with an unlimited number of registers that represent the functionality of the heterogeneous program.

The reader **210** creates an IR **220** from an executable component (EXE) **201**. The reader **210** is a two-stage process as shown in FIG. 2B. First, the executable **201** is parsed **211** into its basic blocks of code and data using information provided in a program database file (PDB) **202**. As well-known in the art, a basic code block is defined as a code block having a single entry point and a single exit point. In an alternate embodiment, all the work performed by the parser **211** is input directly into the second stage of the reader **210**, thus skipping the parsing process.

Once the code and data blocks are identified, an IR creation process **212** evaluates each platform-dependent instruction on a block-by-block basis. There are very large set of common instructions regardless of architecture, i.e., move, store, add, etc., that can be represented by a single platform-neutral IR instruction. For RISC (reduced instruction set computer) architectures, most, if not all, instructions can be easily translated into a single platform-neutral IR instruction. On the other hand, CISC (complex instruction set computer) architectures, such as the Intel x86 family, contain complex instructions that provide the function of multiple instructions. In one exemplary embodiment, the platform-dependent instructions that have a single platform-neutral IR instruction counterpart are translated into that platform-neutral instruction, while complex instructions are replicated as-is within the IR through an extended version of the basic IR instruction. A replicated complex instruction is marked with a signature that denotes its architecture. The output translator **240** recognizes a signed complex instruction and processes it as described further below. In an alternate embodiment, a complex instruction is represented by a set of platform-neutral IR instructions that perform the equivalent function.

After the instructions in the code blocks have been translated, the IR creation process **212** creates a logical hierarchical view of the executable **201** as illustrated in FIG. 3. All architectures share the basic concepts of instructions **305**, code blocks **304**, data blocks **306**, components **302**, and procedures **303**, so the IR hierarchy **300** enables the user to understand the structure of the intermediate representation of a heterogeneous program **301**. The code blocks are logically connected as specified in the EXE file **201** so that the blocks can be more easily manipulated during the transformation process **230**. Procedures are determined by following the logical connections using information provided in the PDB file **202**. Procedures are collected together to create the program components. Little or no optimization of the program is performed by the creation process **212** since it is desirable that the intermediate representation be as close to what the programmer originally wrote as possible.

However, tracing the logical connections to determine the procedures can result in more procedures being created than originally coded by the programmer as described in the related "Translation and Transformation" patent application. Therefore, the creation process **212** annotates, or "decorates," the hierarchy **300** with the user names supplied in the symbol table for the EXE **201**. The annotations enable the user to understand how the IR control flows and how the elements of the IR hierarchy correspond to the procedures and the components in the original code so the appropriate transformations can be applied to the IR. The annotations are maintained in data structures for the procedures during the transformation process and output by the output translator **240**.

At the end of the creation of the IR hierarchy, all instructions are represented in the hierarchy as IR instructions within code blocks so that there is no differentiation between code written for one platform and code written for a second platform. The creation of the IR and an exemplary embodiment of the IR hierarchy are described in detail in the related "Translation and Transformation" patent application.

Once the intermediate representation is complete, the user is allowed to manipulate the code and data (illustrated by the IR transformation module **230**) through an application program interface (API) **250**. The exemplary embodiment of the system **200** provides some pre-defined tools **231** (FIG. 2C) used to instrument and optimize the IR that are guaranteed to be safe in that the tools will evaluate a change requested by the user and only manipulate the code in an appropriate manner. The API **250** also permits the user direct access **232** to the IR to navigate through the IR and to make changes, such as moving blocks between procedures, modifying blocks, rearranging the logical connections between blocks, and changing the platform-specific instruction set for a code block. The tools **231** are described in detail in the related "Instrumentation and Optimization Tool" patent application. The API **250** is described in detail in the related "Application Program Interface" patent application.

By instrumenting the IR using the tools **231**, the user can now watch the interrelationship between the various components of a heterogeneous program and determine if a block of code contained in one component is heavily used by another component, and therefore that block of code should be moved out of the first component and placed into the second component to speed up execution. This process is described in detail in the related "Shared Library Optimization" patent application. Alternately, the user may decide to copy, instead of move, the code into the second component, a process referred to in the art as "code replication." A common optimization technique called "inlining" utilizes code replication.

The transformed IR is now input into the output translator **240**. The output translator **240** operates on the IR in two phases as shown in FIG. 2D: a linker phase **241** that resolves the logical connections into absolute addresses in an address space for a modified version of the executable, and a writer phase **242** that assembles the IR into the modified version of the executable (EXE') **203**. The blocks in the executable **203** can be emitted by the writer **242** for their original platform, or can be emitted for a different platform.

The linker **241** must maintain the semantics of the code of the hierarchy when resolving the addresses, i.e., preserve the logical connections between blocks and the location of referenced data. The linker **241** determines the size of each code block based on the length of each instruction in the block. The linker **241** is also responsible for adding whenever prologue and epilogue code necessary to "glue" together contiguous blocks that will be assembled into different platform-dependent instructions. As part of the address resolution, the linker **241** also can perform limited code modification or optimization. For example, assume that prior to the transformation process **230**, there was a jump between two code blocks, but those blocks are now contiguous. In this case, the linker **241** removes the now-unnecessary jump and lets the logic flow fall through to the second block. Because the hierarchy extends down to the instruction level and is consistent regardless of the manipulation performed by the user, the linker **241** has more knowledge of the placement of instructions than did the programmer. Thus, in architectures in which instructions have both a long and short form depending on the location they are addressing, the linker **241** chooses the appropriate instruction size, which can be a better choice than that originally made by the programmer.

The writer **242** assembles each IR instruction into its platform-dependent counterpart based on the architecture specified in the code block. In an exemplary embodiment in which complex instructions are replaced in the IR, if the complex instruction is being written to the same platform, the writer **242** merely emits the instruction. If the complex instruction is designated to be translated into a different architecture, the writer **242** creates the appropriate set of platform-specific instructions to perform the same function as the original, complex instruction.

As part of the EXE' **203**, the writer **242** creates an emitted block information data structure containing the annotations created by the reader process **210** for each block in the executable. This allows the EXE' **203** to be iterated through the entire process **200** as many times as desired (represented by phantom arrow **260** and described in the related "Translation and Transformation" patent application), while enabling the user to distinguish the original procedures from those added in a previous iteration. In an alternate embodiment, the emitted block information is combined with the PDB file **202** to create a new version of the program database file (PDB') **205** (shown in phantom). The output translation process **240** is described in detail in the related "Cross Module Representation" patent application.

In an alternate exemplary embodiment of the translation and transformation system **200** not illustrated, the IR containing the absolute addresses assigned by the linker **241** is used as input into the IR creation process **212** for further iteration through the system **200**. One of skill in the art will immediately appreciate that much of the work performed by the creation process **212** as described above can be skipped when iterating the modified IR through the system **200**. This embodiment allows the user to transform a heterogeneous program in stages rather than having to make all the changes in a single pass through the system **200**. The system level overview of the operation of an exemplary embodiment of the invention has been described in this section of the detailed description. A translation and transformation system translates a binary component into an intermediate representation, provides an application program interface through which a user can transform the intermediate representation, and translates the intermediate representation as transformed by the user into a modified version of the binary. While the invention is not limited to any particular arrangement of modules, for sake of clarity exemplary set of modules has been described. One of skill in the art will readily recognize that the functions attributed to the modules described in this section can be assigned to different modules without exceeding the scope of the invention. Furthermore, although the translation and transformation of only one input component (EXE 201) has been illustrated and described above, the system can take multiple components, and accompanying PDB files, as input.

Methods of Exemplary Embodiments of the Invention

In the previous section, a system level overview of the operations of exemplary embodiments of the invention was described. In this section, the particular methods performed by a computer executing such exemplary embodiments are described by reference to a series of flowcharts. The methods to be performed constitute computer programs made up of computer-executable instructions. Describing the methods by reference to a flowchart enables one skilled in the art to develop such programs including such instructions to carry out the methods on a suitable computer (the processor of the computer executing the instructions from computer-readable media). FIGS. **4**A–C illustrate the acts to be performed by a computer executing an exemplary embodiment of a linker/writer method that performs the output translator process **240** shown in FIGS. **2**A and **2**D. A heterogeneous program contains at least one component, shown in FIG. **2**A as EXE **201**, that is translated into an IR hierarchy **220**. After any desired transformations **230** are performed on the IR hierarchy **220** by a user, the exemplary embodiment of the linker/writer method **400** takes each component at a time and translates the IR instructions in the component into platform-specific instructions as shown in FIG. **4**A. The linker/writer method **440** relies on the information contained within the IR hierarchical elements that represent instructions, blocks, procedures and components (as described in the related "Translation And Transformation" patent application) to determine what processing is required. In the exemplary embodiment, the acts represented by blocks **401**–**404** are performed by the linker module **241** shown in FIG. **2**D, while the acts represented by blocks **405**–**406** are performed by the writer module **242**. The acts represented by block **403** are described in detail with reference to FIGS. **4**B and **4**C.

The linker/writer method **400** begins by determining if the user has substituted any new code blocks for original code blocks in the component (block **401**) during the transformation process **230** (FIG. **2**A) as illustrated in FIG. **5**. In such a situation, the transformation process **230** leaves code block A **501** in the IR for the component as a placeholder. In one embodiment, the linker/writer method **400** walks through the IR, finding each entry point reference **502** to block A **501** and replacing the entry point reference **502** with the entry point reference **504** to block B **503**. In an alternate embodiment also shown in FIG. **5** in which block A is supplemented but not wholly replaced in the transformation process, a call to block A **501** is redirected to block B **503**. Block B **503** performs its functions, concluding with a jump **505** back to block A **501** so the contents of block A **501** can be executed. In both these embodiments, block A **501** remains in the IR. In yet another alternate embodiment, the linker/writer method replaces code block A **501** with code block B **503**, making block A a "phantom" block.

Also at block **401**, the linker/writer method automatically rebuilds the necessary data structures that are specific to the binary output file format. For example, regarding Win32 PE (Portable Executable) images, the imports, exports, and thread local storage (TLS) sections are rebuilt using the information stored in the IR hierarchy data structures.

The linker/writer method **400** next performs a consistency check on the code blocks in the IR to preserve the semantics of the original control flow among the code blocks (block **403**). Referring to an example provided by FIG. **6**A, blocks A **601**, B **602**, C **603**, and D **604** were originally arranged as shown at **600** with the control flowing from A **601** to B **602** to C **603** to D **604**. In the IR **610**, the block order is A **601**, D **604**, B **602** and C **603**. Therefore, logical linkages are created at block **403** to maintain the original control flow through blocks as shown. Certain optimizations also can be performed at block **403**, such as eliminating the jump between blocks B **602** and C **603** in the IR **610**.

The linker/writer method **400** also determines if two contiguous code blocks in the component are to be emitted for different platforms and creates the prologue and epilogue glue code necessary to transition from one instruction set to another as illustrated in FIG. **6**B. In the original component **620**, blocks A **601**, B **602**, and C **603** were all written for the same architecture. However, during the transformation process **230**, the user marked code block B **602** to be translated into a different instruction set to produce code block B' **605** in the output binary. The linker/writer method **400** inserts the IR instructions for prologue B' **606** and epilogue B' **607** before and after the IR instructions for block B' **605**. Assume, for illustration purposes, that the original component was written in the Intel x86 instruction set but that the user determined that block B **602** would be more optimally written as byte codes for a virtual machine (VM). The IR block hierarchical element is changed to reflect the new architecture. As it walks through the blocks of the component, the linker/writer method **400** keeps track of whether a block is to be emitted for a different platform than that for which it was originally written. The amount of work needed for such a transition is directly proportional to how different the two architectures are. In the present example, IR instructions representing a call to the interpreter for byte codes is added as the prologue B' **606**, and this becomes a new entry point (entry') **609** for the block. The call to the interpreter allows the interpreter to get the starting address of the byte codes relative to the beginning of the component **630**. Calls from other x86 code blocks to the block B' **605** can skip the call to the interpreter in the prologue B' **606** and jump directly into the byte codes at entry point **608** (native entry point).

The prologue B' **606** and epilogue B' **607** perform the necessary register mapping between the two architecture and adjust the shared stack upon entry and exit from the block B' **605** when the output binary is executed.

The linker/writer method **400** also preserves the semantics of the code flow in architectures in which some instructions, such as a loop instruction, have only a short form and thus cannot reference addresses past a certain relative distance. If in the process of doing a transformation on the IR, additional code was inserted in between blocks in the IR so that a loop instruction can no longer operate properly, block **402** of the linker/writer method **400** inserts indirection code to allow the short form to finction while maintaining the block structure that was introduced by the transformation. In one embodiment, the indirection code comprises a block within the short form addressing range that contains a long form jump instruction to the loop instruction's original target. The loop instruction addresses the jump instruction, and the jump instruction jumps to the target block.

Now that all the blocks have been properly linked and any necessary glue code added, the linker/writer method **400** assigns absolute addresses in an address space for the modified executable EXE' **203** (FIG. **2A**) to the blocks in the IR and resolves the logical connections to the appropriate absolute addresses (block **403**). In the exemplary embodiment, the processing at block **403** begins by initially assigning an optimal fixed size to each code block whose size could fluctuate (due to certain instruction long and short formats). The size for a data block is fixed and will never change. The optimal fixed size for a code block is computed based on the average number of instructions per block multiplied by the average instruction size. In one embodiment, the average number of instructions per block is 3.2 and the average instruction size is 2.5 bytes, giving an optimal fixed size of 8 bytes. This initial size assignment allows the linker/writer method **400** to perform forward referencing on blocks that have not yet been assigned working or absolute addresses as described next.

The absolute address assignment is performed through two major processing loops. The first or "priming" loop is illustrated in FIG. 4B. The priming loop assigns working addresses to the blocks that represent a displacement relative to the start of the component to initially approximate the block address. For those instructions that have both a long form and a short form ("relative instructions"), the priming loop assigns the short size. After the priming loop has assigned working addresses to each of the blocks, the second or "verification" loop illustrated in FIG. 4C, reevaluates the size of the relative instructions and creates the absolute addresses. Some relative instructions that were originally assumed to be short form may need to change to long form because their target reference is now further away than originally calculated using the initial average sizes for the blocks. Once the priming loop has assigned fairly accurate sizes to the blocks, those relative instructions that are likely to require the long form can be determined by the verification loop with little or no error.

Turning now to FIG. 4C, the priming loop begins by setting a "currentaddress" variable to the starting address of the component (block **410**). Each block in the component is examined (block **411**) and assigned a starting address equal to the current value in the currentaddress variable (block **412**). If the block is a data block (block **413**), the currentaddress variable is recalculated to be at the end of the data block using the pre-determined size for a data block (block **414**).

If the block is a code block (block **413**), each instruction in the code block is examined (block **416**) to determine if it is a relative or regular instruction (block **417**). A relative instruction is assigned the short form size (block **418**). The size of a regular instruction is calculated (block **419**). The size of each instruction is stored in the IR element that represents the instruction. In the exemplary embodiment, the short form size is two bytes and the calculation of a regular instruction is performed by calling the appropriate assembler to emit the instruction so the actual size of the instruction can be determined. The appropriate assembler is specified in the IR block element; the calling of the assembler is described further below. The currentaddress variable is recalculated to take into account the instruction's size (block **420**).

When all instructions (block **421**) in all blocks (block **415**) in the component have been examined, every instruction and block has been assigned a working size, and every block has been assigned a relative working starting address.

In an alternate embodiment in which the binary is divided into sections and each section must be assigned on a particular byte boundary, the priming loop is performed on a section by section basis throughout the entire IR, readjusting the starting address of the first block in each section to lie on the correct boundary.

The verification loop illustrated in FIG. 4C checks for the correctness of the size of all relative instructions within the component. If no size adjustments are required, the working addresses are the correct addresses and no address recalculation needs to be done. Therefore, the verification loop uses a "stop" flag to determine that no change is required. If the value of the stop flag is true when the verification loop has reexamined each instruction in the component, no recalculation is necessary.

The verification loop examines each block in the component (block **433**). If it is a code block (block **434**), each instruction in the code block is examined to determine if it is a relative instruction (block **436**). A new size for each relative instruction is calculated using the working block sizes assigned by the priming loop (block **437**). If the new size is different than that stored in the corresponding IR instruction element, i.e., long rather than short, (block **438**), the new size is stored (block **439**) and the stop flag is set to false to indicate that the block sizes and addresses must be recomputed.

Once all instructions (block **441**) in all code blocks (block **442**) have been reexamined, the currentaddress variable is set to the starting address of the component (block **443**) and the stop flag is tested (block **444**). If the stop flag is true (block **444** and **431**), the working addresses assigned by the priming loop are correct and become the absolute addresses for the component.

If the stop flag is false (block **444**), at least one relative instruction has changed in size from short to long, so its block has changed size and the addresses of all blocks within the component must be recalculated. Each block in the component is once again examined (block **445**) and its address recomputed based on the new sizes for the instructions (block **446**). The stop flag is set to true (**448**) when addresses have been recomputed for all the blocks (block **447**) to end the verification loop. At this point the IR is complete with absolute addresses. If a relative instruction changes from the long form to the short form, the linker/writer method **400** does not revert back to the short form because this would introduce an infinite loop in the process. By prohibiting an instruction from shrinking back, the assign addresses loop illustrated in FIG. **4**B is guaranteed to converge and terminate within a "reasonable" time period.

Returning now to FIG. **4**A, the linker/writer method **400** creates, or updates, the emitted block information data structure (**204** or **205** in FIG. **2**A) for each block (block **404**). One exemplary embodiment of the emitted block information is shown in FIG. **7** as having a block header **715** and a set of symbol table entries **720**. The block header **715** contains a block address field **701**, a block size field **702**, an alignment field **703**, and a set of flags **704**–**710**. The block address field **701** is the absolute address for the block within the component assigned by the verification loop in FIG. **4**C. The block size field **702** contains the size of the block computed by the verification loop. Table 1 defines the flags **703**–**709** for the present exemplary embodiment of the header.

TABLE 1

Flag	Block Type	Description
IsData	Code or Data	defines block as code or data
IsCallTarget	Code	whether block contains an entry point for a procedure
IsInstrumentable	Code	whether block can have instrumentation added by user
IsUnreachable	Code or Data	whether block can be reached from another block in the binary
IsNoReturn	Code	whether block transfers control and does not return to calling block
Alignment	Code or Data	boundary on which to align the block, if any
Assembler	Code	code architecture

The linker/writer method **400** creates a large buffer into which the platform-specified code will be emitted (block **405**). The method walks through the IR block by block, calling the appropriate assembler to emit the code as defined within the IR block element. For IR instructions that fit a basic format, such as "load," "store," or "add," the linker/writer method **400** submits the appropriate parameters to the assembler and the assembler passes back the corresponding platform-specific instruction, which is placed within the buffer at the address for the instruction. For IR instructions that do not fit the basic format, referred to as extended version or mode IR instructions, the IR instruction element is marked the signature flag of the original architecture. The linker/writer method **400** first determines if the instruction is to be emitted for its original platform. If so, the appropriate parameters from the IR instruction element are passed to the assembler just as with the basic format IR instruction. If the architecture is changing, the linker/writer method **400** uses an translation data structure, such as a hash table, to determine a set of basic format IR instructions that perform the function of the extended mode IR instruction. Each of those IR instructions is passed into the assembler to be emitted as the corresponding platform-specific instruction. There is a translation data structure for each architecture supported by the system and each translation data structure contains entries for only those platform-specific instructions that cannot be represented by the basic IR instruction form. The translation data structures are created outside the system and the information contained therein will be readily apparent to one skilled in the art. An exemplary embodiment of the IR instruction elements in both the basic form and extended version is described in detail in the related "Translation and Transformation" patent application.

After the buffer has been fully populated with instructions for the binary, at block **405** the linker/writer method **400** also updates the source and target addresses that are stored within a symbol table or a program database (PDB file **205** in FIG. **2**A) that contain entry points, export entry tables, jump tables, and symbol tables. In one embodiment the information for a source or target address is a displacement into a block instead of being the first address within the block.

The linker/writer method **400** concludes by writing out the buffer to an output file specified by the user to serve as the binary for the component (block **406**). The emitted block data structures **700** are written to the output file for the binary (as illustrated by emitted data block information **204** in FIG. **2**A) or to the PDB file **205**. Additional internal use information is also written to the output file at this time. In one embodiment in which the emitted block information is stored in the output file, the internal use information specifies the offset within the output file at which the emitted block information begins. The internal use information can also contains data such as extended debugging information. In another embodiment in which the emitted block information is written to a separate file, such as the PDB file **205**, the internal use information is written to the same file. In yet another alternate embodiment, the internal use information is written to a completely separate file that is associated with the emitted block information file.

The particular methods performed by computer in executing an exemplary embodiment of the output translator **240** have been described with reference to flowcharts including all the acts from **401** until **406**, **410** until **421**, and **430** until **448**. In addition, an exemplary embodiment of an emitted block information data structure created by the output translator **240** has been illustrated.

Conclusion

An output translator has been described that provides for cross module representations of components within a heterogeneous program. The heterogeneous program is translated into an intermediate representation that is a hierarchy of platform-neutral elements that correspond to instructions, code blocks, procedures and components within the program. Blocks of instructions that were originally written for one architecture can be translated from the intermediate representation into platform-specific instructions for a different architecture. The output translator provides any necessary prologue and/or epilogue code to interface contiguous code blocks that are emitted in different instruction sets. Furthermore, for an architecture that has both short and long forms for instructions, the output translator initially assumes the emitted instruction will be in its short form and only substitutes the long form when required, the output code can be more compact than using the long form as the default output format. The choice of the short form for the default also introduces efficiencies into the output translator process because working relative addresses assigned by the priming loop are highly likely to be the absolute address within the output binary, reducing the number of iterations that must be performed to emit the code. Finally, because the code blocks within the components can be translated into different architectures than they were originally written enables faster execution of the program.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement which is calculated to achieve the same purpose may be substituted for the specific embodiments shown. This application is intended to cover any adaptations or variations of the present invention.

For example, those of ordinary skill within the art will appreciate that the division of the output translator into a linker and a writer module, and the methods that each perform, can be allocated differently without changing the functions performed by the output translator. Furthermore, those of ordinary skill within the art will appreciate that the translation from the IR instructions into the platform-specific instructions can be accomplished through the use of look-up tables, hashing function, or database records.

The terminology used in this application with respect to is meant to include all of these architectural environments. Therefore, it is manifestly intended that this invention be limited only by the following claims and equivalents thereof.

We claim:

1. A computerized method for translating a heterogeneous program into different architectures comprising:

reading a heterogeneous program having a plurality of executable components in different forms;

obtaining a platform-neutral intermediate representation of a component in the heterogeneous program;

creating logical linkages among a plurality of code blocks in the intermediate representation of the component to establish a control flow through the component;

assigning an absolute address within an address space for the component to each of the plurality of code blocks;

resolving the logical linkages to the absolute addresses for the corresponding code blocks;

emitting a platform-specific executable instruction for each instruction represented in the intermediate representation of the component into a buffer; and

writing the buffer to an output file to create a new version of the component.

2. The computerized method of claim 1, further comprising:

inserting interface code between contiguous code blocks having instructions emitted for different architectures.

3. The computerized method of claim 1, further comprising:

replacing an entry point to a first code block with an point to a second code block introduced by a user to substitute for the first code block.

4. The computerized method of claim 1, further comprising:

generating information defining an emitted block; and

associating the emitted block information with the new version of the component.

5. The computerized method of claim 1, wherein assigning an absolute address comprises:

assigning a working address and working size to each block in the intermediate representation of the component;

assigning the working address as the absolute address if the working size of each code block is accurate for a corresponding emitted code block; and

calculating the absolute address if the working size of each code block is not accurate for the corresponding emitted code block.

6. The computerized method of claim 5, wherein assigning the working address and working size comprises:

determining an emitted size for each instruction in each code block that is a regular instruction; and

assigning a fixed size for a short form of each instruction in each code block that is a relative instruction.

7. The computerized method of claim 6, wherein the working size of each code block is accurate for the corresponding emitted code block if the short form is valid for each relative instruction within the code block.

8. The computerized method of claim 1, wherein emitting a platform-specific instruction comprises:

inputting parameters defining the intermediate representation of the instruction to an assembler; and

storing the corresponding platform-specific instruction generated by the assembler into the buffer.

9. The computerized method of claim 8, further comprising:

obtaining the parameters from a translation data structure.

10. The computerized method of claim 1 wherein obtaining comprises:

parsing an executable component in the heterogeneous program into basic code blocks; and

creating an intermediate representation of the basic code blocks, the intermediate representation comprising a hierarchy of instructions.

11. The computerized method of claim 10 wherein the step of creating an intermediate representation comprises:

annotating the intermediate representation with user names.

12. A computer-readable medium having computer-executable instructions to cause a computer to perform an output translation method on an intermediate representation for a component comprising:

resolving logical references within the intermediate representation to absolute addresses in an address space for the component;

emitting instructions for the component in a plurality of platform-specific instruction sets defined by the intermediate representation; and

inserting interface instructions in the intermediate representation between code blocks marked to be emitted in different platform-specific instruction sets, the interface instructions enabling a transition from one platform-specific instruction set to a different platform-specific instruction set.

13. The computer-readable medium of claim 12, wherein resolving logical references comprises:

creating working addresses for a plurality of code blocks in the intermediate representation;

assigning absolute addresses for the plurality of code blocks based on the working addresses; and

resolving each logical reference to one of the plurality of code blocks to the absolute address for the one of the plurality of code blocks.

14. A computer-readable medium having stored thereon an emitted block information data structure for describing a code block emitted by a cross-module representation system, the data structure comprising:

an address field containing data representing a starting address for the emitted block;

a size field containing data representing a size of the block starting at the address in the address field;

a flag field containing data representing a set of information flags for the block starting at the address in the address field; and

a symbol entry containing data representing a symbol name and a symbol address for a symbol appearing in the block starting at the address in the address field, wherein the emitted block and the data structure are accessible by the cross-module representation system to facilitate optimization of the emitted block.

15. The computer-readable medium of claim **14**, further comprising:

an alignment field containing data representing an alignment boundary for the address in the address field.

16. The computer-readable medium of claim **14**, wherein the information flags are selected from the group consisting of:

a call target flag;

a begin procedure flag;

a no split flag;

an instrumentable flag;

an unreachable flag;

a data flag; and

a no return flag.

17. A computerized system comprising:

a processing unit;

a system memory coupled to the processing unit through a system bus;

a computer-readable medium coupled to the processing unit through a system bus;

a reader module reading a heterogeneous program comprising a plurality of executable components written for two or more computer architectures;

a platform-neutral intermediate representation of the heterogeneous program in the system memory; and

an output translator module executed from the computer-readable medium by the processing unit, wherein the output translator module causes the processing unit to translate the intermediate representation into a set of platform-specific instructions that accomplish the function of the heterogeneous program.

18. The computerized system of claim **17**, wherein the set of platform-specific instructions includes subsets of platform-specific instructions with the subsets being for different platforms.

19. The computerized system of claim **18**, wherein the output translator module further causes the processing unit to insert at least one platform-neutral instruction in the intermediate representation to provide an interface between the subsets of platform-specific instructions.

20. The computerized system of claim **17**, wherein the output translator module further causes the processing unit to translate at least one instruction in the intermediate representation into a platform-specific instruction different than a corresponding platform-specific instruction in the heterogeneous program.

21. The computerized system of claim **17**, wherein the output translator module further causes the processing unit to activate a platform-specific assembler to generate the set of platform-specific instructions.

22. A computer-readable medium having computer-executable instructions stored thereon for performing a method comprising:

reading a heterogeneous program comprising a plurality of executable components written in two or more instruction sets;

translating an intermediate representation of the heterogeneous program into a set of platform-specific instructions; and

writing the platform-specific instructions onto a computer-readable medium to create a new version of the heterogeneous program.

23. The computer-readable medium of claim **22**, wherein translating the intermediate representation comprises:

emitting an instruction in the intermediate representation into a platform-specific instruction different than a corresponding platform-specific instruction in the heterogeneous program.

24. The computer-readable medium of claim **23**, further comprising:

inserting interface instructions in the intermediate representation between contiguous instructions emitted for different platforms.

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